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Development Of A Figure-of-Merit For Space Missions

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ABSTRACT

The concept of a quantitative figure-of-merit (F-o-M) to evaluate different and competing options for space missions, is further developed. Over six hundred individual factors are considered at the time of this report. These range from mission orbital mechanics to In-Situ Resource Utilization (ISRU/ISMU) plants. The program utilizes a commercial software package for synthesis and visual display; the details are completely developed in-house. Historical FoM's are derived for successful space missions such as the Surveyor, Voyager, Apollo,... A cost FoM is also mentioned and will be further developed. The bulk of this work is devoted to one specific example of Mars Sample Return (MSR). The program is flexible enough to accommodate a variety of evolving technologies. Initial results show that the FoM for sample return is a function of the mass returned to LEO, and that missions utilizing ISRU/ISMU are far more cost effective than those that rely on all earth-transported resources.

INTRODUCTION

The variables in a space mission are so numerous and their interactions so complex that it is not easy to visualize the overall mission impact of many components. Frequently, we are faced with difficult choices that must consider competing technologies, anticipated advances, expected improvements in reliability, and the overall life-cycle costs that could easily run into hundreds of millions of dollars. For initial screening purposes, it was felt highly desirable to develop an overall figure-of-merit (FoM) for the mission that could be used for ranking these competing candidates. When one recognizes that the parameters vary from orbital mechanics to rocketry, and chemical plant masses to the power source reliability, the difficulty of accurately combining these becomes apparent.

Work was initiated last year on this difficult task. The input parameters were divided into four major categories: the mission, transportation, ISRU/ISMU plants, and the support systems. The feasibility of developing a meaningful FoM was proven. The quantitative examples included various MSR missions that clearly showed the advantages of ISRU/ISMU [reference 1]. It was felt desirable to further develop this highly useful concept. One of the main aims this year was to tie this concept to the current SERC work on the oxygen plant design. In addition, the FoM's of various successful

missions were examined within the framework of the software.

Section II describes the input parameters. Section III describes the software development. Section IV presents the principal results. This report concludes with a brief outline of future work and applications.

#### THE INPUT PARAMETERS

The FoM concept organizes the inputs into four major categories and then integrates the dependent variables through the appropriate governing equations. The four categories are loosely described as mission details, rocket design, in-situ resource utilization (ISRU), and support components. The bulk of the inputs pertain to the joint spacecraft and rocket design. This is where most of the flexibility will occur in any given design. The governing equations have been modified to accurately reflect the dependencies of many detailed spacecraft parameters. The categories have been developed and defined as much as possible, but the technology is constantly changing and innovations are always being introduced. It should be stressed here that the FoM is a dynamic property since it directly reflects even minor changes in the mission planning.

#### SOFTWARE DEVELOPMENT

The FoM itself is calculated within a commercial spreadsheet software package. The spreadsheet option was chosen over a programming language due to its ability to integrate either internal or external data and then present the results in simple color graphics. Ease of use is also a major factor, since no knowledge of any programming language is necessary. Only an understanding of the basic equations is required. The spreadsheet structure was completely reorganized to simplify the input process and take full advantage of the three-dimensional capabilities of the software. The spreadsheet equations and structure have been generalized wherever possible to maximize the flexibility of the approach.

Two key emerging technologies have been included in the spreadsheet program. The ISRU concept and the use of modular engines are options now available for the mission planner. Both technologies are innovations that may provide major improvements in mission capabilities. The quantitative effect of either on mission planning can now be calculated in a relative manner.

The ISRU idea is to use local resources whenever possible to help fulfill the mission goals. Exploration of the Earth has historically utilized local resources to succeed, and the natural and logical progression is to apply this concept to planetary exploration also. A proof-of-concept oxygen production plant is being built at the Center for the Utilization of Local Planetary Resources. It is designed to use an electrocatalytic process to convert gaseous carbon dioxide into molecular oxygen. The available data from the Center has been included in the spreadsheet to provide accurate figures for the masses of each component. The projected production rate and total mass

are, therefore, all based on current research directly related to the manufacture of the plant. As the technology matures, the spreadsheet can easily be updated to reflect the improvements.

The use of modular engines will not reduce the initial total mass of the spacecraft as the use of ISRU will. However, the other direct benefits will have an overall effect of increasing the FoM. The benefits to be gained from modular engines are increased reliability, reduced risks, simpler reparability. There is even the important added benefits of a reduction in both design and production costs. The spreadsheet has been configured for the possible use of modular engines for the return voyage. The size of the engine is dictated by the thrust required for the last staging maneuver. The number of engines needed in a cluster for all previous stages is based on this one engine. All the calculations are done automatically. The current limit imposed on the modular engine design is the restricted use of propellants. Only fuels and oxidizers that do not need refrigeration for the return voyage in space can be utilized.

A propellant database has also been incorporated into the overall scheme for the calculation of the FoM. The database has been constructed in another commercial software package with which the spreadsheet can form a direct link. All of the pertinent performance parameters have been input for a total of twenty-six different propellant combinations. The parameters that have been varied for each database record are the chamber pressure, oxidizer to fuel ratio, and the nozzle area ratio. For each of these various combinations, the chamber temperature, characteristic velocity, specific impulse, pressure ratio, and vacuum specific impulse have also been input. Special thermodynamic data is being included in the spreadsheet for each propellant in the database so the storage parameters can be automatically calculated. Only by knowing the specific volume of both the fuel and oxidizer can the tanks be sized accurately. The database, of course, could be used for other projects, but its sole use until now is for the FoM spreadsheet.

## RESULTS

The FoM definition is allowed flexibility in order to apply to almost any mission architecture. A set of definitions has been devised, and a few of them have been applied to historical U.S. space missions. To date, only technical definitions have been utilized. Cost definitions have been identified and would be very useful, but the difficulty in gathering accurate accounting data has caused many problems. The application to historical missions has identified the usefulness of using different definitions depending on the type of mission. For example, the definition used in a sample return mission is defined as the mass of the payload returned to low-Earth orbit (LEO) divided by the initial spacecraft mass starting in LEO. It was important to factor in the mass of the sample for this type of mission, but of course, this parameter did not apply to previous orbiter missions. In essence, the flexibility of the FoM concept was tested within a historical context and given a certain validity that will hopefully also apply to any future missions. In an effort to quantify all important

aspects of a planned mission, all the definitions factor in a multiplier to account for variations in reliability, reparability, and risk.

The spreadsheet has been developed sufficiently to handle a rigorous analysis of a Mars Sample Return (MSR) mission. The following graphs show some preliminary findings in the analysis. The FoM is defined in both graphs as

$$FoM = \frac{\text{Sample Mass}}{\text{Initial Mass in LEO}} \times [R_{\text{factor}}] \times 10^4$$

where

$$R_{\text{factor}} = (\text{Inverse Risk}) \times (\text{Reliability}) \times (\text{Reparability})$$

The first graph presents the FOM for a range of payload masses to be returned to LEO. The small masses represent a typical sample mission with the larger masses possibly representing an evolution of manned missions. A series of different propellant combinations is shown with some including the use of ISRU. The important thing to note is that the maximum FoM within each mass category is always accomplished by using ISRU. The second plot shows the typical variation in mission strategies for a MSR mission. The relative gains realized through the use of modular engine configurations and with ISRU, both separately and together, are presented. Two propellant combinations are shown for comparison. The benefits attained using both technologies may not seem greatly significant on the surface, but in terms of the sample mass, even small improvements are very important.

## FUTURE WORK

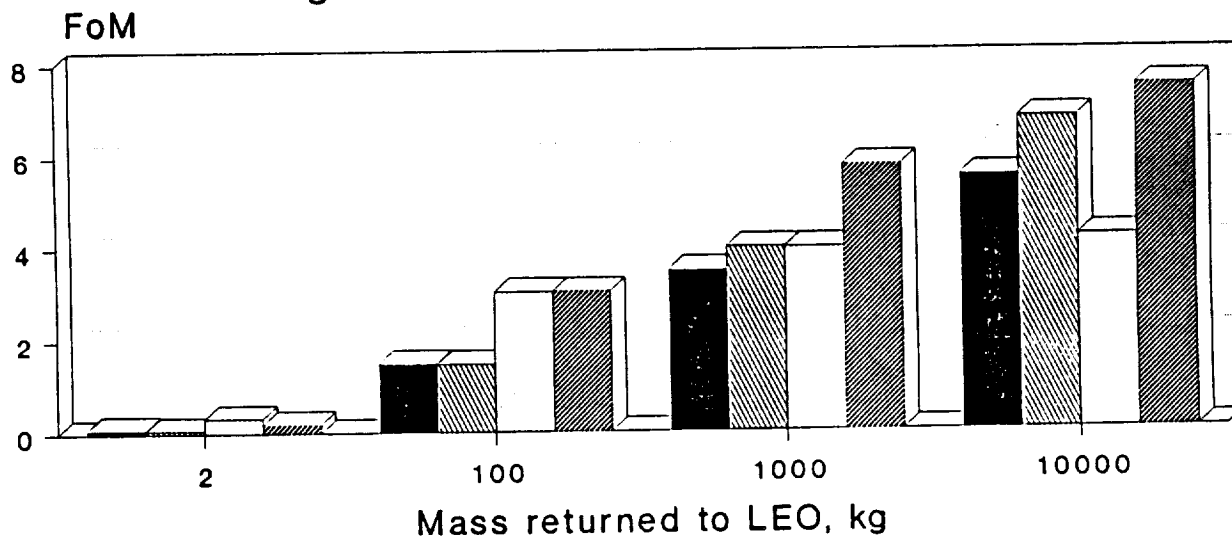
The FoM methodology is fairly unique since it identifies promising mission architecture from the initial planning stages before focusing on more detailed design. The spreadsheet is configured for a MSR mission, and since a mission of this type is only in the planning stages at this point in time, it would be ideal to analyze any preliminary results the FoM can provide. The previous results are interesting in their own right, but a much more detailed analysis is still to be accomplished. All the propellants in the database need to be analyzed to determine possible hidden advantages in an overall framework. In addition, many of the spacecraft design variables should be varied to help focus on a more beneficial design. Both strong and weak correlations need to be identified between related input parameters, and further overall optimization needs to be accomplished.

REFERENCES

1. K.N.R. Ramohalli, B. Preiss, and T. Kirsch, "A Figure-of-Merit Approach to Extraterrestrial Resource Utilization," paper no. IAA 89-716 at 40th Congress of the International Astronautical Federation, 1989, also accepted in AIAA Journal of Propulsion and Power, 1990.

# MARS MISSION VARIATIONS

Figure-of-Merit vs. Returned Mass



■ H2+O2 (All-Earth Carried)

▨ H2+O2 (ISRU O2)

□ CH4+O2 (ISRU O2)

▩ H2+O2 out/CH4+O2 in (ISRU O2)

LEO = 500 km altitude

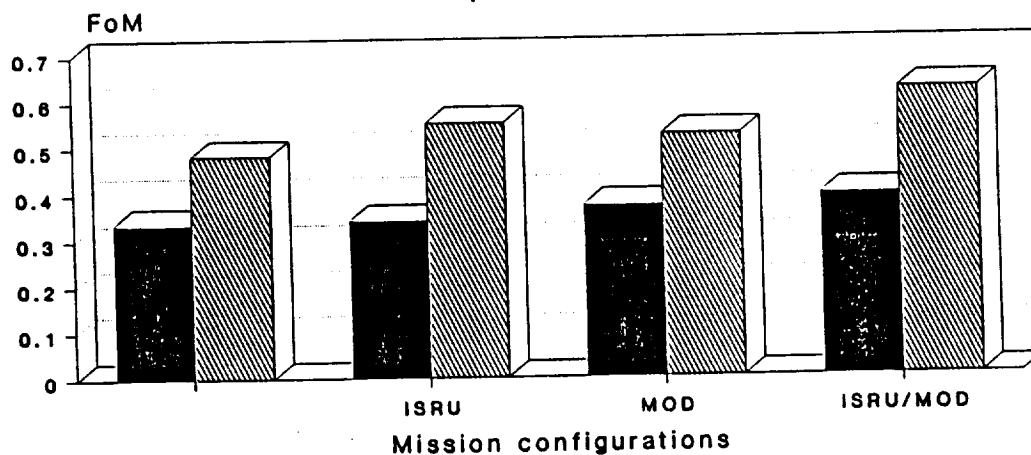
ISRU = In-situ resource utilization

$$\text{FoM} = [(M \text{ sample}) / (M \text{ LEO})] \cdot R \text{ factor} \cdot 10^4$$

$$R \text{ factor} = \text{Inverse Risk} \cdot \text{Reliability} \cdot \text{Reparability}$$

## MARS SAMPLE RETURN VARIATIONS

Sample Mass = 4 kg



■ H2+O2 outbound/CH4+O2 Inbound

▨ CH4+O2 (All Stages)

MOD = Modular engine use

ISRU = In-situ resource utilization